Approximate Analysis and Design of Conventional Industrial Facilities Subjected to Bomb Blast Using the P-i Technique

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ABSTRACT

Efforts to characterize the response of complex structural systems to the intense transient loads generated by bomb blast can involve significant computational effort. Additionally, the practitioner must have a substantial amount of experience to interpret the results of these analyses. Unfortunately, when facilities are subject to terrorist attacks, sufficient time is often not available for detailed analysis.

Southwest Research Institute (SwRI), under contract to the US Army Corps of Engineers at Omaha and the Naval Civil Engineering Laboratory at Port Hueneme, California, has been developing simplified procedures for the prediction of damage to conventional buildings generated by airblast transient loads. In these methods component damage is first calculated for each component in the building using pressure-impulse curves (P-i curves). The P-i curves relate non-dimensional terms calculated using the component geometry, material strength, material stiffness, and boundary condition, and the peak applied blast pressure and impulse, to component damage. The P-i curves were developed theoretically using an energy approach and then shifted, where necessary, to match measured damage data. The theoretical curves are shifted to match damage data in regions where the damage is overpredicted.

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In the second step of these procedures, building response is calculated by summing component damage. Several summation algorithms have been written which calculate percentage of overall damage to the building, the amount of reusable floor space, the repairability of the building, and the level of protection provided by the building for a given explosive threat.

1.0 Introduction

A general procedure for determining the vulnerability of common industrial buildings to explosion threats has been established and is outlined in this paper. This procedure is essentially a two-step process where, first, damage to each component in the building is determined using P-i diagrams, and then damage from all the components in the structure is summed to determine overall building damage. The key features of the procedure include the development of the P-i curves which correlate the blast load and component structural properties to component damage and the summing algorithms used to add up component damage and determine building response. The procedure has been programmed into a computer code, called BDAM, and the code has been used to calculate damage to a number of different buildings, considered "typical" of commonly constructed buildings, from a wide variety of explosive threats. The key features of the blast vulnerability analysis procedure are described in this paper and some results of damage calculated to common building types from given explosive threats are shown.

2.0 P-i Curve Use

The general procedure for determining building vulnerability that is outlined in this paper is based on the calculation of building member response using P-i curves. P-i curves, or pressure-impulse curves, are used in the procedure because they can be programmed easily into a computer code and because they were used in the initial work on this procedure to describe measured component response in terms of component properties and blast loading parameters. Work on simplified vulnerability analysis of industrial facilities began at SwRI several years ago with an effort sponsored by the Naval Civil Engineering Laboratory (NCEL) to develop a procedure which predicted damage for common construction components based on available data. P-i curves were chosen as the basic tool for this purpose. Damage data was plotted against theoretical P-i curves (developed using with energy methods) and when the data did not agree with the curves, the curves were shifted, or "calibrated" to overlay the measured damage points as closely as possible. An ongoing effort at Southwest Research Institute (SwRI) is the improvement of the theoretical P-i curves to include all the types of strain energy that affect member response (such as compression and tension membrane action) so that damage data will match better with theoretical curves.

Figure 1 shows a typical P-i diagram which can be used to calculate the level of dynamic response in terms of level of protection for two-way concrete slabs (the relationship between level of protection and component response parameters such as ductility ratio is defined later in the paper). The protection levels shown in the margin of the diagram apply throughout the diagram between

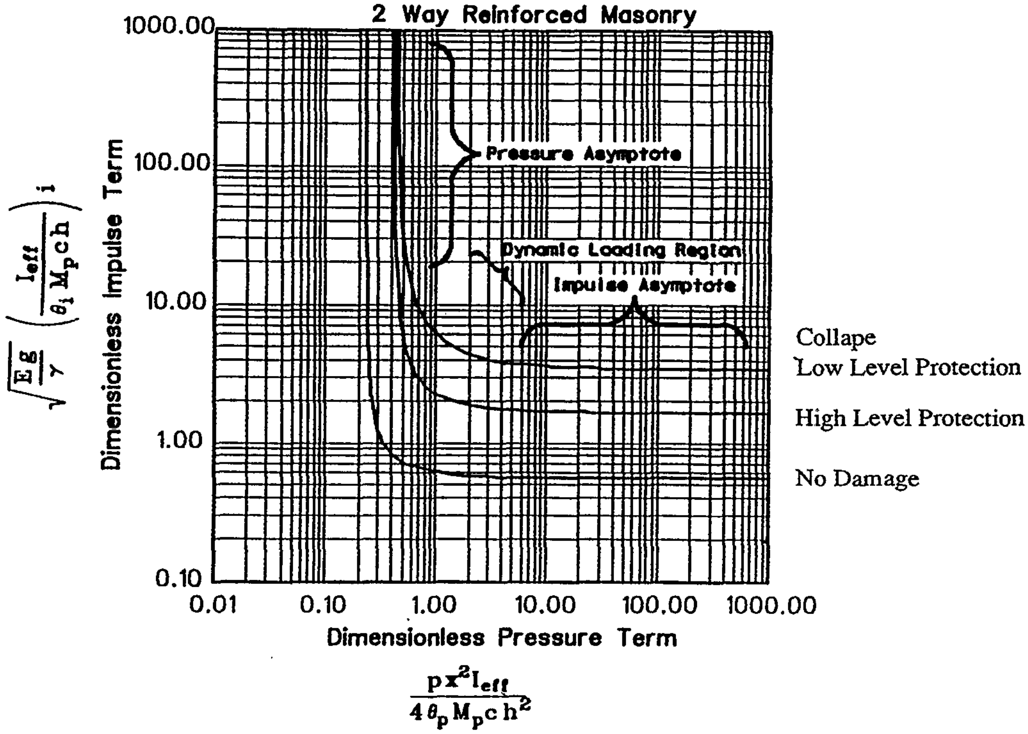


Figure 1. Example P-i Curve

the curves. The terms on each axis are made up of blast loading parameters, the peak pressure (p) and the blast load impulse (i), and slab structural parameters, such as the plastic moment capacity (M_p) and characteristic span length (l). The level of protection provided by the slab is determined by calculating the non-dimensional terms on either axis of the P-i diagram and reading the protection level off the diagram based on the location of the point defined by the two terms. In cases where detailed information about the structural parameters are unknown, approximations can be made. The curves assume a given shape of the blast load history, a right triangular load history for all the P-i curves used in the procedures discussed here, and are only valid for load histories with the assumed shape.

P-i curves are different from other similar tools used to calculate dynamic response to blast loads, such as time-stepping computer programs or other types of charts showing dynamic response, in that the portion of the dynamic response that is affected only by the peak load is separated from that which is independent of the peak load and only affected by the time integral of the applied load (the impulse). This is due to the manner in which loading history parameters and structural member geometry and physical property parameters are grouped into algebraic terms and plotted against each other to make up the P-i curves. Often, it is advantageous to the designer to know the extent to which impulse or the peak load affects member response since the effectiveness of various design strategies depends on the which loading parameters are controlling dynamic response. Another distinct feature of P-i diagrams is the simple shape of the response curves. This feature is advantageous to the implementation of P-i curves into computer codes since the response curves can typically be described with a single equation that connects the two asymptotic values.

Figure 1 shows these distinct features. The figure shows the two basic loading parameters, the peak pressure and the impulse, are separated into the two terms along the axes. In the portion of the curves which is perpendicular to the horizontal axis, the level of response (or protection) is controlled only by the horizontal axis term which indicates that, in this portion of the curves, response is controlled only by the peak load and not by the impulse. This is labeled as the quasistatic region in Figure 1. The opposite is true in the portions of the curves perpendicular to the vertical axis, which are labeled as the impulsive region. In the portions of the curves perpendicular to neither axis, the response is dependent to some extent on both loading parameters, and this region is labeled as the dynamic region in Figure 1. The simple shape of the response curves is also shown in the figure.

P-i curves based on damage data have been developed for a variety of structural components which are representative of those expected in common industrial buildings. Table 1, which is presented later in this paper, lists all these structural components. For some components no damage data from explosive loading was located in the literature and theoretical P-i curves are used. References 1 and 2 document this work.

The P-i curves assume a given type of structural response (e.g. flexural response, buckling). Some structural elements fall under more than one type of P-i diagram as more than one mode of failure is possible for these members. The components for which there is more than one failure mode include:

- Open web steel joists
- Exterior columns (all)
- Interior columns (all)

Open Web Steel Joists - Two modes of failure are possible: tension failure of the bottom cords and web buckling. P-i diagrams are provided for each failure mode. The user should calculate the protection level using each diagram and accept the lesser of the two values.

Exterior Columns - These elements can fail due to bending induced from exterior blast loading or by deformations due to frame sway of the structure. First, use the P-i diagram for a column in bending to obtain a protection level. Second, use the frame P-i diagram to obtain a protection level. Use the lesser level of protection provided.

Interior Columns - These elements can fail due to either buckling or frame sway. Since buckling is simply a fail/no fail condition, the P-i diagram for column buckling for dynamic axial loads is used first to determine if the element will fail or not. If it does not fail due to buckling, then the diagram for frame response is used to determine the protection level provided by the columns.

The following are a variety of comments concerning various structural components and how they are addressed in analysis.

Non-Arched and Arched Sections - P-i curves are provided for one-way masonry and two-way reinforced concrete components for both the non-arched (NA) and fully arched (FA) cases. Arching is the contribution of compressive membrane effects to the resistance of the section in flexure. Arching can be considered when the supporting structure of a component provides in-plane resistance, or resistance to in-plane translation during response. Specific cases include concrete frame structures with in-fill masonry walls (arched walls), or in-fill two-way concrete walls. When it is not apparent that arching can develop, the non-arched figures should be used. It is always conservative to use the non-arched case.

Columns - A structure can have interior and exterior columns. This guide considers response modes of buckling for interior columns, but not exterior columns. Exterior columns are loaded directly by the blast wave and can respond in bending. The damage caused by bending response is expected to cause more severe than that caused by buckling for most cases. It takes a relatively large load to induce buckling failure, and such a load will easily cause bending response failure in the column. The P-i diagrams are based on the assumptions that interior columns are unsupported over each story height and are not laterally loaded to a significant extent by any of the blast wave which "leaks" inside the building.

For structures which have moment resisting frames, the frame mode of response needs to be accounted for in the analysis. Both interior and exterior columns can contribute to the frame stiffness if they are moment resisting. Only those that are moment resisting should be included. Direction is given on the P-i diagrams on how to calculate the strengths and mass of framed structures.

Doors, Windows, and Cement-Asbestos Corrugated Panels - For these structural components, P-i diagrams are not provided since these elements are considered to be pressure sensitive only. The suggested failure criterion is 2.0 psi. Above this value, these elements are considered to have failed; below this value, they survive.

Finally, end conditions of components (i.e., "fixity") can be specified if not completely known using the guidance provided in Reference 4. Localized response experienced by structural elements due to very close-in or contact detonations is not considered by the P-i diagrams.

3.0 Component Damage Evaluation

Two different sets of categories have been used to describe the level of component and building response in blast vulnerability assessment projects at SwRI. In previous work performed by SwRI for the Naval Civil Engineering Laboratory (NCEL) (References 1, 2), four damage categories generally were defined for each structural element. They were:

Slight Damage -- damage level 0, (0% damage)

Moderate Damage -- damage level 0.3, (30% damage)

Severe Damage -- damage level 0.6, (60% damage)

Failure -- damage level 1.0

These damage levels corresponded to damage observed in tests used to adjust the theoretically determined energy solution curves or "P-i" curves. They are used to characterize component and building response in the blast vulnerability procedures developed for NCEL. The inputs required to analyze the blast damage to each component with P-i curves are explained in detail in the "Blast Vulnerability Guide" (1) developed for NCEL by SwRI. The guide provides easy-to-follow calculation procedures which allow engineers estimate blast damage to structural components using hand calculations for a wide range of explosive threats. Figure 2 shows a P-i diagram which describes the response of a wood roof subjected to blast loading in terms of the four damage levels shown above.

In subsequent work for the US Army Corp of Engineers at Omaha (COE), a different set of categories were used to define component damage in terms of component utility. For vehicle bomb and exterior attacks, the COE "Security Engineering Manual" (SEM)[3] defines three levels of protection.

They are:

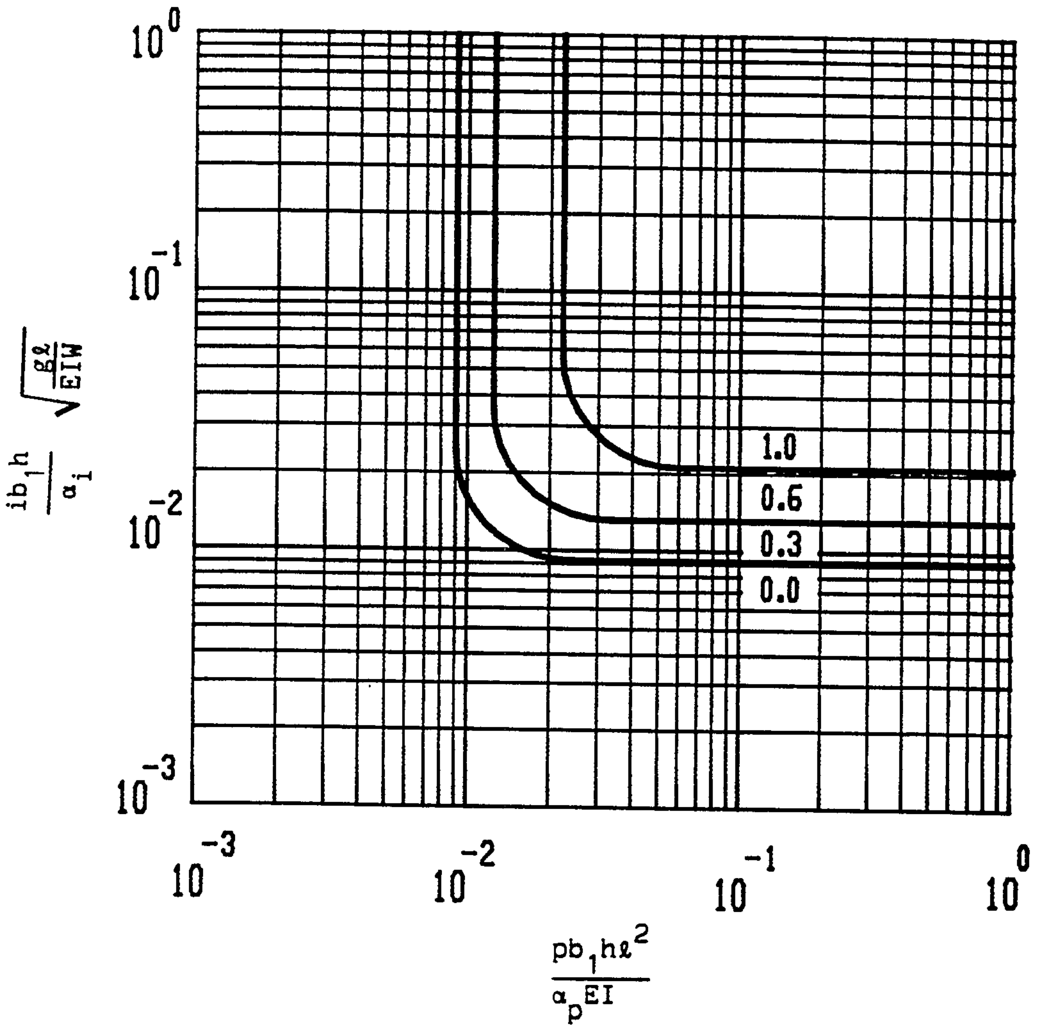
Low Level of Protection -- unrepairable structural components, a high level of damage without collapse

Medium Level of Protection -- repairable structural components, a significant degree of damage

High Level of Protection -- superficially damaged

The adjustment required to use the P-i curves developed for NCEL, which are based on the 30%, 60%, and failure damage levels, to define Low, Medium and High protection levels described in the SEM is based on component utility. Table 1 lists the 25 components which can be analyzed with P-i curves and indicates whether the component is judged to be repairable at a certain damage level. Note that the R's indicate a repairable component, while the U's indicate a component requiring replacement. This table was developed during work for NCEL because the Navy wanted building response described in terms of both damage level and reusability.

Particular attention was given to the fact that the steel components generally are shown to require replacement at the 30% damage level. As discussed in Reference 2 however, this requirement is more of a suggestion, since "(steel members) are relatively easily and inexpensively replaced;



Boundary Conditions	α_i	α_p
Simple-Simple	1.4610	8.0
Fixed-Simple	0.8944	8.0
Fixed-Fixed	0.8944	12.0

Figure 2. Pressure-Impulse Relation for Wood Roofs Showing Response to Blast Loads in Terms of Damage Levels

Table 1. Repair/Replace Factors Recommended in the Reference 2

Structural Component	Damage Level			
	0.0	0.3	0.6	1.0
R/C Beams	R	R	R	U
R/C One-Way Slabs	R	R	U	U
R/C Two-Way Slabs	R	R	U	U
R/C Exterior Columns (bending)	R	R	R	U
R/C Interior Columns (buckling)	R	R	R	U
R/C Frames	--	--	--	--
Prestressed/Post-tensioned planks	R	U	U	U
Steel Beams	R	U	U	U
Metal Stud Walls	R	U	U	U
Open Web Steel Joists (web failure)	R	U	U	U
Open Web Steel Joists (chord failure)	R	U	U	U
Corrugated Metal Deck	R	U	U	U
Steel Exterior Columns (bending)	R	R	U	U
Steel Interior Columns (buckling)	R	R	U	U
Steel Frames	--	--	--	--
One-Way Unreinforced Masonry	R	R	U	U
Two-Way Unreinforced Masonry	R	R	U	U
One-Way Reinforced Masonry	R	R	U	U
Two-Way Reinforced Masonry	R	R	U	U
Masonry Pilasters	R	R	U	U
Wood Stud Walls	R	R	U	U
Wood Roofs	R	R	U	U
Wood Beams	R	--	--	U
Wood Exterior Columns (bending)	R	--	--	U
Wood Interior Columns (buckling)	R	--	--	U

Note: R = repairable, U = unrepairable

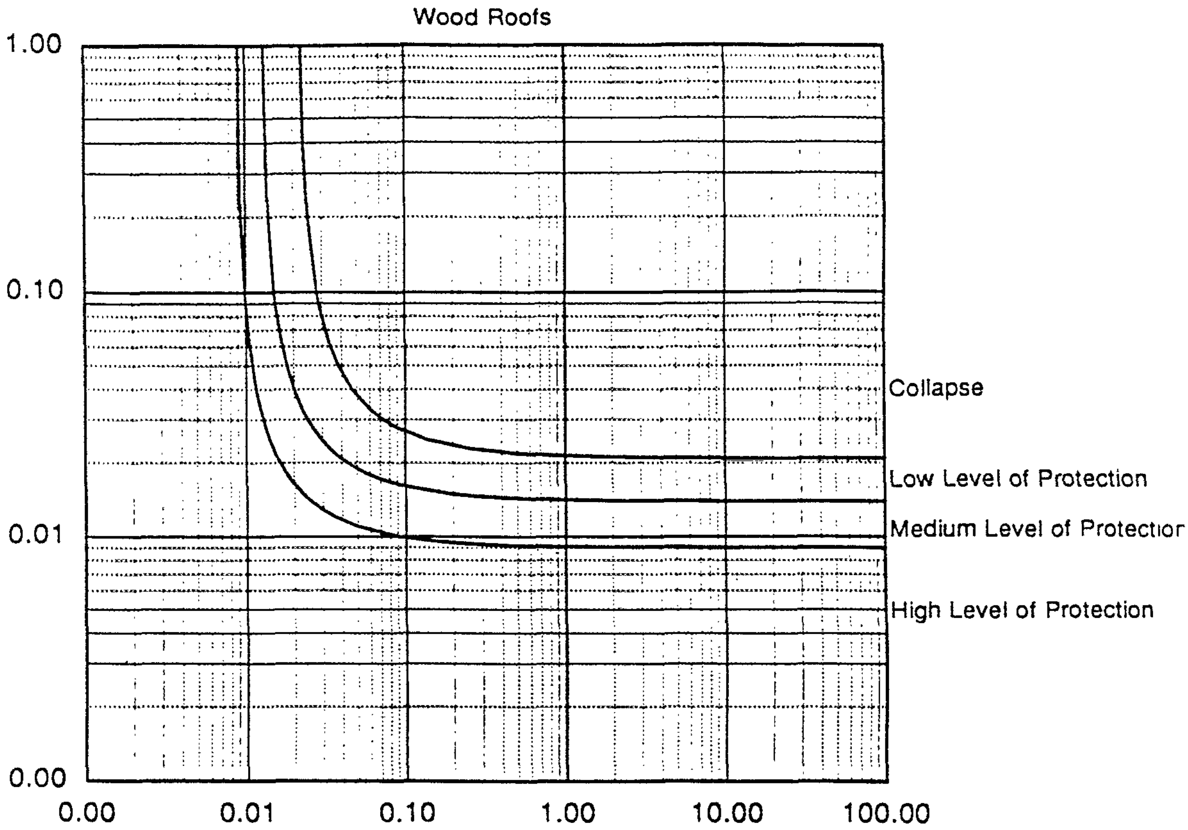
hence, we chose to require replacement for damage levels of 0.3 and above." Thus, it could be interpreted that the steel components may *not* require replacement at the 30% level, but will require replacement at the 60% level.

These repair/replace suggestions were used to translate the P-i curves based on damage levels into curves corresponding directly to SEM protection levels. The following correlation was defined:

> *Low Level of Protection* -- this level is indicated on the P-i curves by all values falling below and to the left of the threshold line dividing 60% damage and failure and above and to the right of the threshold line dividing 30% and 60% damage. The upper limit for a low level of protection generally corresponds with the 60% damage level.
>
> *Medium Level of Protection* -- this level is indicated on the P-i curves by all values falling below and to the left of the threshold line dividing 30% damage and 60% damage and above and to the right of the threshold line dividing 0% and 30% damage. The upper limit for a medium level of protection generally corresponds with the 30% damage level.
>
> *High Level of Protection* -- this level is indicated on the P-i curves by all values falling below and to the left of the threshold line dividing 0% damage and 30% damage. The upper limit for a high level of protection generally corresponds to the 0% damage level.

Figure 3 shows a P-i diagram which describes the response of a wood roof to blast loading in terms of the three protection levels shown above. Reference 4 shows the P-i curves which relate level of protection to the non-dimensional terms on the axes of the P-i diagrams. In this reference the inputs required to determine the level of protection provided by the structural components listed in Table 1 using the P-i curves developed at SwRI are explained in detail and easy-to-follow calculation procedures are provided which allow engineers to estimate blast damage to structural components using hand calculations for a wide range of explosive threats. There are numerous example problems. Default values which can be used as inputs when detailed structural information is not available are also listed.

In summary, two different approaches to characterize component damage have been used in the building blast vulnerability procedures developed at SwRI. Basically these two approaches are based on the same damage data and are equivalent to each other except for the nomenclature used to describe component response. Table 2 shows how the High, Low, and Medium protection levels used in work for the COE are defined in the more generally used response terms of deflection to length ratios (w/l's) and ductilities (μ's). Since the level of protection terms used by the COE correlate closely with the percentage of damage terms used for NCEL, Table 2 also indicates the correlation between deflection values and ductilities and percentage damage levels shown at the top of this section.



$$\sqrt{\frac{g\,l}{E\,I\,W}}\ \frac{i\,b_1\,h}{\alpha_i}$$

$$\frac{p\,b_1\,h\,l^2}{\alpha_p\,E\,I}$$

Boundary Conditions	α_i	α_p
Simple-Simple	1.4610	8.0
Fixed-Simple	0.8944	8.0
Fixed-Fixed	0.8944	12.0

Figure 3. Pressure-Impulse Relation for Wood Roofs Showing Response to Blast Loads in Terms of Level of Protection

Table 2. Comparison Between Protection Level and Deflection and Ductility Response Criteria

Structural Component	Proposed Damage Criteria						Notes
	High Protection Level		Medium Protection Level		Low Protection Level		
	μ	w/l	μ	w/l	μ	w/l	
R/C Beam	1	.01	5	.02	20	.035	
R/C One-Way Slabs	1	.01	5	.02	20	.035	Same as R/C beam
R/C Two-Way Slabs	1	.002	5	.008	20	.134	Both unarched (no compressive membrane effects and arched (w/compressive membrane effects)
R/C Exterior Columns (bending)	1	.01	5	.02	20	.035	Same as R/C beam
R/C Interior Columns (buckling)	--	--	--	--	--	--	
R/C Frames	3	.02	6	.04	12	.08	
Prestressed/Post-tensioned T-beams and slabs	.2	--	.5	--	1	--	
Steel Beams	2	.0087	7	.033	15	.067	
Metal Stud Walls	2	.0087	7	.033	15	.067	Same as steel beams
Open Web Steel Joists (web bending failure)	1	.0083	3.5	.017	6	.033	Same as steel beams
Open Web Steel Joists (chord buckling failure)							

Table 2. Comparison Between Protection Level and Deflection and Ductility Response Criteria (continued)

Structural Component	Proposed Damage Criteria						Notes
	High Protection Level		Medium Protection Level		Low Protection Level		
	μ	w/l	μ	w/l	μ	w/l	
Corrugated Metal Deck	2	.0087	7	.033	15	.067	Same as steel beams
Steel Exterior Columns (bending)	2	.0087	7	.033	15	.067	Same as steel beams
Steel Interior Columns (buckling)	--	--	--	--	--	--	
Steel Frames	3	.02	6	.04	12	.08	
One-Way Unreinforced Masonry (unarched)	1	--	1	--	1	--	Wall becomes unstable when deflection approaches the wall thickness
One-Way Unreinforced Masonry (arched)	.25	--	.5	--	1.0	--	
Two-Way Unreinforced Masonry	.1	--	.15	--	.25	--	All considered fully arched
One-Way Reinforced Masonry	1	--	5	--	20	--	Same as R/C beam
Two-Way Reinforced Masonry	1	--	5	--	20	--	Same as R/C slab
Masonry Pilasters	1	--	5	--	20	--	Same as R/C beam
Wood Stud Walls	1	--	2.2	--	4.4	--	
Wood Roofs	2.0	--	2.8	--	4.4	--	
Wood Beams	1	--	1	--	4.4	--	
Wood Exterior Columns (bending)	1	--	1	--	4.4	--	
Wood Interior Columns (buckling)	--	--	--	--	--	--	

4.0 Building Vulnerability Assessment

The preceding sections explain how component damage is calculated. This section describes how several measures of overall building response are calculated with the blast vulnerability procedures. Two separate types of summation algorithms for summing component damage and determining overall building response have been used because NCEL and the COE have used the blast vulnerability methods to assess blast damaged buildings for different end purposes. NCEL has been more concerned with overall, or average damage and the need for building repair or replacement, while the COE has been concerned with the level of protection provided by the most damaged portion of the building.

4.1 Building Damage Assessment Procedures Developed for NCEL

Separate procedures to calculate the total building damage, a building reusability factor, and a building repairability factor for a given explosive threat were developed for NCEL. In these procedures the damage level of each component is first calculated as described in the preceding section, and then building response is determined using different summation algorithms. The procedure to calculate total building damage begins by weighting each component based on the importance of the component to the overall integrity of the building structure, and then summing the product of the damage level of each component multiplied by the weighting factor. This sum is divided by the weighted sum of all components corresponding to total building destruction. This fraction is the total building damage and it is usually expressed as a percentage. The summing algorithm used to determine building damage assumes that, if any component fails (100% damage), all members supported by this component also fail. This is referred to as cascading failure. Component weighting is determined primarily according to how other many members are supported by the component in question (e.g. columns are weighted more heavily than beams).

The results of an evaluation made using this procedure with the same charge weight at several standoffs can be used to determine building damage as a function of explosive separation distance and plotted as a "damage function" for that particular charge weight. Several damage functions can be plotted on the same graph. The explosive amounts which can be considered range from a few ounces of TNT for a typical hand grenade up to 4000 pounds for a large bomb.

The component damage levels are also used to determine the building reusability factor. This factor, which can be used to determine how much of the building is reusable prior to repair, is equal to the percentage of usable floor space in the damaged building. In this procedure it is assumed that floor space is nonreusable only if a component beside or over that area incurs 100% damage. Finally, the building repairability factor is calculated based on the calculated component damage levels and the assumed relationships between damage level and repairability in Table 1. The sum of all the weighting factors of all unrepairable components is divided by the sum of the

weighting factors of all components and this ratio is called the repairability factor. If the factor is greater than 0.5, rebuilding is recommended rather than repair. This factor provides a recommendation as to whether the building should be repaired or rebuilt for a given explosive threat.

Twelve building types considered to be representative of common industrial facilities were "designed" by SwRI so that the damage that was likely to be incurred by common buildings exposed to various explosive threats could be calculated. During subsequent work for the COE a thirteenth common building was added. These common buildings, each of which represent a "category" of buildings common to a naval or army base, are summarized in Table 3. Doors and windows in all buildings are assumed to be of standard construction. These non-hardened doors and windows are assumed to fail at low pressures.

Building damage functions (percent building damage plotted against standoff for a given explosive threat), building reusability functions, and building repairability functions were calculated for each common building in Table 3 and these functions are included in Reference 2. Figures 4, 5, and 6 show percent building damage, percent building reusability, and rebuild/repair plotted for three explosive threats at various standoffs to Building No. 6 in Table 3.

In order to automate the work involved in assessing building vulnerability to blast loading with these procedures, SwRI developed the computer program BDAM. The P-i curves and the summation algorithms that calculate each type of building response described above (damage, reusability, and repairability) are programmed into the code. Thus, the BDAM code automates the procedure of calculating component and building damage so the user can determine the vulnerability of a building if he/she is given the weight and location of the explosive and the structural characteristics of all components comprising the building as determined by on-site surveys and structural drawings. The final output of the BDAM code includes total building damage, repair/rebuild factors, and the percentage of usable area of the building. The code will also output a summary of the damage to each individual component. Details of the input and output to the code are included in Reference 5.

4.2 Security Engineering Manual (SEM) Approach Developed for the COE

Subsequent to the NCEL work, the US Army Corps of Engineers Omaha District (COE) contracted SwRI to improve the P-i curves for concrete and masonry components, to simplify the building damage summation procedure, and to redefine the building damage in terms of that described in their SEM as described in Section 2. Improvement of the P-i curves is an ongoing effort where new data is used as it becomes available to obtain better correlation between damage predicted by the P-i curves and measured values. Improvement efforts have also included a reformulation of the theoretical P-i curves for some components to include strain energy absorbed in response modes other than flexural response (e.g. compression membrane response) which has resulted in a better agreement between theoretical P-i curves and damage data for these components.

Table 3. A Summary of Building Types and Categories

Building No.	Category
1	One-story, large (> 6000 ft^2), reinforced concrete building.
2	One-story, small (< 6000 ft^2), reinforced concrete and reinforced masonry building.
3	One-story, small (< 6000 ft^2) unreinforced masonry building.
4	One-story, small (< 6000 ft^2), unreinforced clay brick building.
5	One-story, small (< 6000 ft^2), metal stud wall building.
6	Two-story, small (< 6000 ft^2), reinforced concrete building.
7	One-story, small (< 6000 ft^2), pre-engineered (Butler® type) building.
8	One-story, large (> 6000 ft^2) metal stud wall building.
9	Two-story, small (< 6000 ft^2), timber building.
10	One-story, large (> 6000 ft^2), tilt-up reinforced concrete building.
11	One-story, large (> 6000 ft^2), heavy timber building.
12	Two-story, large (> 6000 ft^2), steel frame building.
13	One-story, large (> 6000 ft^2), prestressed concrete (double "T") building.

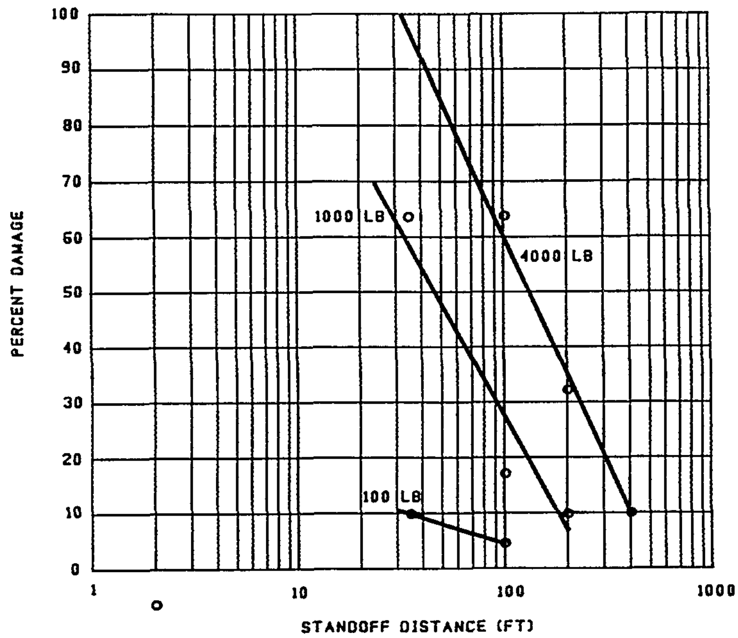


Figure 4. Percentage Building Damage to Building No. 6 Calculated for Given Explosive Threats

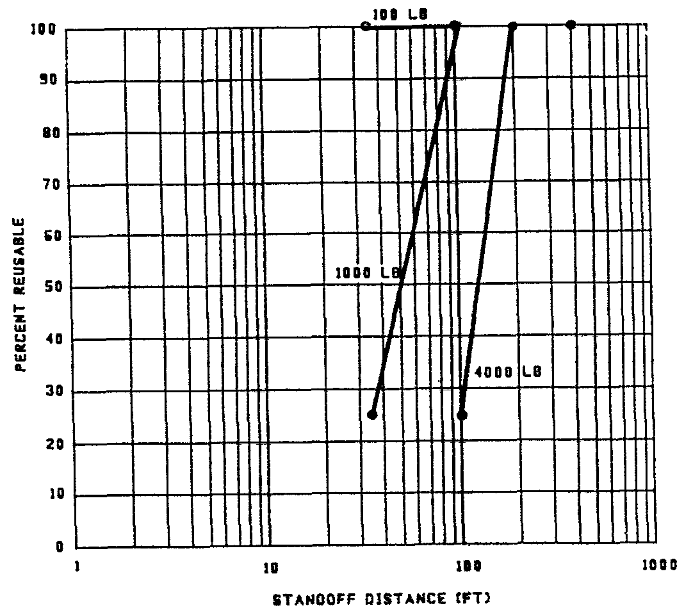


Figure 5. Percentage of Reusable Floor Space in Building No. 6 Calculated for Given Explosive Threats

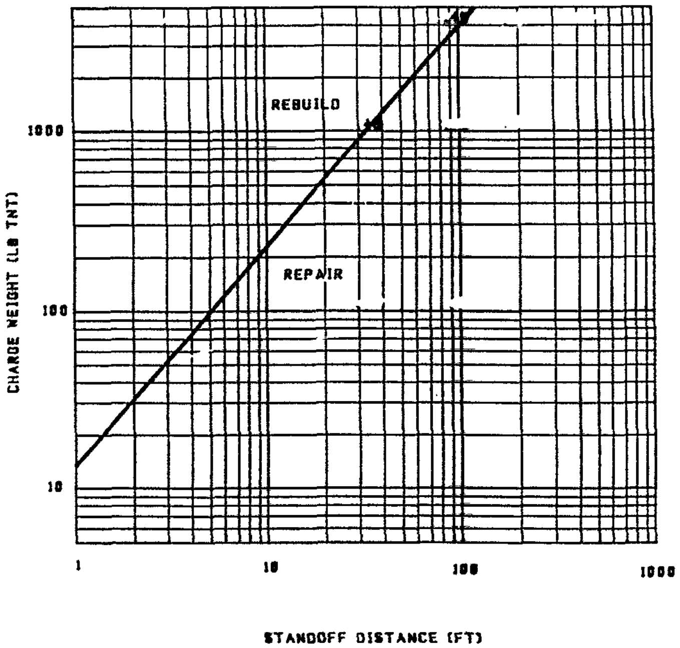


Figure 6. Rebuild/Repair Relationship for Building No. 6 Calculated for Given Explosive Threats

The method for determining building damage originally presented in the NCEL work was reviewed and determined not suitable for use when building response in terms of protection level provided. The criteria required by the SEM considers the damage of *any* component at a given protection level to determine the protection provided by the whole facility. Therefore, the summing algorithms used in the building damage procedures developed for NCEL were not applicable. The following definitions of building damage level were generated:

> *Low Level of Protection* -- this level corresponds to a charge weight and standoff combination that generates damage no more severe than that associated with a low level of protection for any component anywhere in the facility. This excludes door and window components.
>
> *Medium Level of Protection* -- this level corresponds to a charge weight and standoff combination that generates damage no more severe than that associated with a medium level of protection for any component anywhere in the facility. This excludes door and window components.
>
> *High Level of Protection* -- this level corresponds to a charge weight and standoff combination that generates damage no more severe than that associated with a high level of protection for any component anywhere in the facility. This excludes door and window components.

The criteria and resulting curves were incorporated into two computer based algorithms. The first algorithm predicts building *damage* as described in Section 4.1. The second algorithm computes building *protection level* based on any component reaching a prescribed protection level (damage) at a particular standoff for a given charge weight. Buildings 1-13 in Table 3 were analyzed using these algorithms. Figure 7 shows a comparison between percentage building damage as calculated using the method described in Section 4.1 and protection level as prescribed in the SEM for Building No. 6 in Table 3.

The final product of this work for the COE was a set of building protection level curves. These curves are shown in Reference 4 for the thirteen typical structures in Table 3. They can be used for an estimate of structure protection level if the cases under study are of similar construction to one of the common building types. The accuracy in applying these curves depends directly upon how closely the structures in question compare with the structures represented by the curves. In general, if the dimensions (i.e., spans, roof height, column spacing) of the structure are within 25% of those described for each building type, and the materials (wall thickness, roof type, etc.) are similar (within 15% of thickness or depth) the protection level curves may be generally applied to similar buildings. Building plan dimensions are not as critical. A wide range of plan sizes and aspect ratios (length to depth ratios) can be analyzed with the curves.

The following steps can be taken to conduct an analysis using the building protection curves:

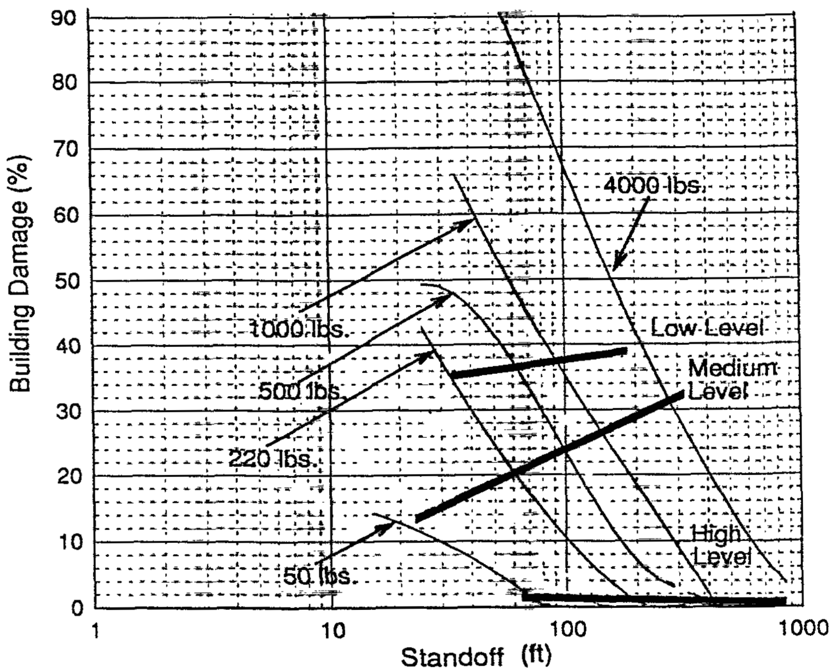


Figure 7. Comparison of Percentage Building Damage to Building Level of Protection for Building No. 6 Subjected to Various Explosive Threats

1. Select the analysis parameters. Determine three of the following four parameters.

   - desired level of protection
   - charge quantity
   - distance from weapon to structure (standoff)
   - orientation to structure (adjacent to long dimension or short dimension of the structure)

2. Define the building type to be analyzed.

   - determine which type closely represents the structure of interest
   - check to make sure story heights, spans, column/beam spacings are generally within 25% of "common" types and that thicknesses and depths are within 15% of "common" types

3. Determine the protection level provided or standoff required by entering the curves. Enter the curve with the appropriate charge weight on the vertical axis, and the

appropriate standoff on the horizontal axis. Read the protection level at the intersection of these lines. Points below and to the right of the low, medium and high curves correspond to protection levels at the indicated level or higher.

The protection level curves present the protection levels provided by the buildings described in Table 3 for different charge weights (TNT equivalent) and standoffs. A typical protection level curve is shown in Figure 8. The dashed lines indicate the protection level provided against an explosive charge placed at a standoff perpendicular to the center of the "short" side of the buildings, or 90° for the "long" side. The solid lines or 0° lines represent the protection level provided for a charge placed at a standoff perpendicular to the center of the building "long side".

The curves should be entered with the standoff in feet and the charge weight in pounds of TNT. The intersection of those points, then, indicates protection level provided. A point to the right and below a curve indicates a level of protection greater than that curve, but less than that of the curve further to the right. Conversely, a point to the left and above a curve indicates a protection level less than that of the curve, but greater than that of the curve to the immediate left. Points to the left of the low level of protection curve indicate structural failure.

On several of the plots the protection level curves do not extend down to lower standoffs. This indicates that the use of the respective Level of Protection (LOP) curve below that standoff is beyond the range of applicability of the analysis used to define the curve. In all cases, scaled standoffs of $R/W^{1/3} = 3.0$ were defined as a lower limit, since response mode changes can occur for certain materials below that standoff. These response mode changes can mean that local breaching or panel shearing could occur at these low standoffs. If local breaching is not important to overall building or asset protection, the analyst can neglect this component response. If the desired or plotted point is in this regime, the protection level provided can be determined as the greater of the values obtained by either moving horizontally to the right along the same charge weight line or vertically up to the next LOP curve.

If the building to be analyzed cannot be compared well with those in Table 3, the level of protection can be calculated by first calculating the level of protection provided by each component in the building using the P-i curves in Reference 4 (see Figure 3 for an example). The use of these P-i curves requires knowledge of structural and geometry parameters describing each component and the peak pressure and impulse applied to each component. Considerable guidance in the calculation of each of these parameters is provided in Reference 4. Then, the level of protection provided by all the components is searched for the lowest level of protection. This lowest level of protection is the building level of protection for the given charge weight and standoff used to calculate the blast loads.

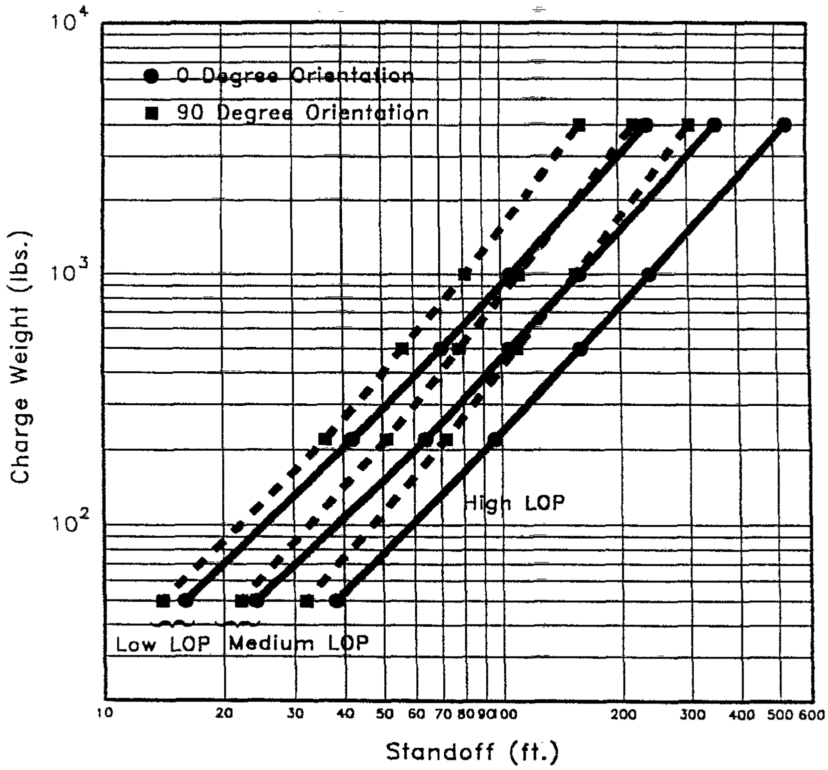


Figure 8. Building No 7 (Small Pre-Engineered "Butler" Type Building) Protection Level Curves versus Charge Weight

5.0 Future Developments

- First and most importantly--any future efforts must begin with additional literature searches to collect data for all components to be considered. In order to truly confirm the analytical resistance functions we postulate for the components--we must validate the predicted response with data for all components.

- Secondly, additional data must be acquired to validate building damage predictions. The most recent work for NCEL included some limited validation of building damage using WW II data that was not really sufficient in detail for analysis. Details of most of the attacks that have occurred over the last ten to twelve years in Britain and Ireland may be available. These documented "data points" should have sufficient detail for analysis.

- Third, we ought to look at the way we calculate collapse--and attempt to come up with a more realistic (in a structural sense) scenario for member collapse and subsequent loss of a building's usable space. There are data and reports available describing collapse. The thing to remember is that engineered structures retain an astonishing amount of load carrying capability even after the loss of "key" members because of strength in secondary structure and sheathing, etc.

- Fourth, <u>response modes other than flexural</u> should be investigated and included in the code or procedure capability. We should start by looking at buckling, shear and local shear (breach).

- BDAM or the code should also be <u>modified to allow analysis or design of individual components</u>. A tool might be developed that can be entered with standoff and charge weight, told what type of construction (concrete, steel frame and sheathing, wood, etc.) the designer wants, and the code will do preliminary sizing, etc.

6.0 Conclusions

The work summarized in this paper demonstrates the usefulness of the P-i approach as a basic method for quickly assessing blast damage to relatively large buildings taking into account the blast response of each component. The P-i curve approach is flexible enough to be used to describe many types of components, ranging from open web steel joists to concrete slabs; many types of response, ranging from buckling to flexural response; and different types of building vulnerability assessment approaches, ranging from a level of protection assessment to a building damage assessment.

The usefulness of the P-i approach is considerably enhanced by the BDAM program developed at SwRI. This computer code reads a description of all the building components and the charge weight and charge locations of interest and quickly calculates damage to all components in the building based on the P-i curves which are programmed into the code and then sums component damage or level of protection according to the set of "rules", or algorithms which are programmed into the code. The code outputs both a detailed component-by-component summary of damage and simple plots which show the total building damage or level of protection as a function of charge weight and charge standoff. Work which is funded by the US Army Corp of Engineers at Omaha is currently underway at SwRI to reduce the effort involved in the input of typical buildings.

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